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Manufacturing and Cost Considerations in Multidisciplinary Aircraft Design

(Research on Mathematical Modeling of Manufacturability Factors)

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Table of Contents

Introduction

The application of multidisciplinary design optimization (MDO) methodology to preliminary aircraft design has traditionally been focused on obtaining the best set of design parameters that minimizes aircraft weight. While lower weight is crucial for improved aircraft performance the process to achieve it must also take into account the manufacturing requirements and costs.

Gutowski *et al.*[1] in a study to determine the weight to cost relation of structures made of advanced composite materials found that the high material, fabrication, and tooling costs may all add up to make the use of such light weight and high performance materials cost ineffective as compared to commonly used metal alloys. This argument is captured by Hirt[2], and is illustrated in Fig. 1 as he discusses the importance of design-to-cost methodology in balancing the performance enhancement through weight reduction with the increase in necessary raw materials and labor costs. Therefore, in selecting a material system for the structure it is important to consider the following: (a) cost of raw materials, (b) cost of tooling of individual components, (c) costs associated with a particular fabrication process and technique, (d) cost of jigging and assembly of the final structure based on the total number of parts and method of assembly, (e) rejection or rework rate, (f) damage tolerance considerations and repair costs, (g) environmental factors based on the toxicity of the materials used, and finally (h) certification issues.

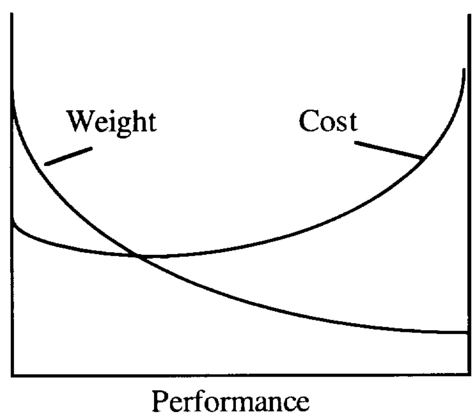


Figure 1. Cost/Weight Tradeoffs

In the June, August, and October 1994 issues of Aerospace America[3-5] there were three articles which to varying degree addressed the topics of cost and manufacturing and their importance in any aircraft design from general aviation to transport jets to military fighters. In the June issue it was mentioned that fabrication accounts for about 70% of the cost of finished composite part. In the August issue it was mentioned that according to industry estimates, 70-80% of an aircraft's cost is fixed at the end of the conceptual design stage. It also elaborated on the importance of concurrent engineering approach to lowering that cost. Other manufacturing improvement and cost reduction measures are promised through design-for-assembly, design-for-manufacture, and design-for-service methodologies. The importance of general aviation revitalization and its link to lowered manufacturing cost has been recognized for several years, and was reiterated in the October 1994 issue of Aerospace America.

Boothroyd *et al.*[6] point out that while design activities make up about 10% of the product cost, they indirectly contribute to about 70% of the product cost. Manufacturability of the product is also mentioned as a major factor influencing quality and cost. Hence, it can be argued that with proper attention to product manufacturing in the design phase, the efforts in the prototyping, test and evaluation, and production phases could be substantially reduced. Inclusion of manufacturing cost in the design process is important when considering that, for example in the case of a composite military aircraft, the airframe manufacturing cost accounts for approximately 50% of the total manufacturing "flyaway" cost and about 30% of the life-cycle cost.[7] Recognizing that aircraft design is a vital part of aircraft development, it becomes clear that factors affecting manufacturability and cost of the aircraft, in parallel to those of weight and performance, need to be considered early in the design process in order to arrive at truly optimal designs. Therefore, in the context of MDO methodology as applied to preliminary aircraft design, manufacturing and cost influence factors combined with structural allowables and performance constraints would form a more rigorous set of requirements — resulting in more realistic optimum designs.

Rais-Rohani and Dean[8] performed a study demonstrating the challenges in the way of modeling and proper integration of manufacturing and cost considerations in multidisciplinary aircraft design.

The focus of current research has been twofold: (1) the identification of airframe Manufacturability Factors/Cost Drivers (MFCD) and the method by which the relationships between MFCD and designer-controlled parameters could be properly modeled and (2) the integration of this models into an MDO-based computational design tool. This report is primarily on the activities related to the first task. The underlying assumption for all the discussions in this report is the availability of process information which could be in the form of databases, manufacturing handbooks, service manuals, etc. Furthermore, no effort is made here to limit any of the discussions to a certain class or group of aircraft, and reference to both metallic and composite structures is made.

Mathematical Modeling of Manufacturability Factors

In order to include manufacturing as a separate discipline in multidisciplinary design of aircraft structures, an attempt is made here to develop mathematical models that relate manufacturability factors to the parameters controlled by the designer. These factors would allow the designer to determine whether or not a particular design could be manufactured. In addition they could provide the designer with the criteria to compare different manufacturable designs in order to identify the one that is the most efficient or optimal. Although the factors described in this report could apply to any product, they are viewed here specifically in terms of aircraft structures.

Manufacturability is defined as the ability to manufacture a product to obtain the desired quality and rate of production while minimizing cost. The manufacturability factors, in their general forms, are grouped into a set of five core manufacturability concepts as described by Shankar and Jansson.[9] The five core concepts and their corresponding categories are identified in Fig. 2.

The five core manufacturability concepts are: compatibility; complexity; quality; efficiency; and coupling. Core 1 (compatibility) seeks to bring focus to compatibility factors among material, configuration, and manufacturing process. Core 2 (complexity) addresses factors such as intricacy, describing the amount of detail in a part, tolerances on geometric dimensions and surface finish, uniformity, accessibility, orientation, and ease of handling for each part. Core 3 (quality) is concerned with reducing design features that can cause critical flaws. It also deals with the robustness of the design with respect to minor variations in material properties and process parameters. Core 4 (efficiency) brings attention to the importance of efficient use of materials, reduction of part count, standardization of parts, and reduction in varieties of parts used in the design. Core 5 (coupling) is concerned with couplings that originate from material characteristics, configuration, and manufacturing process.

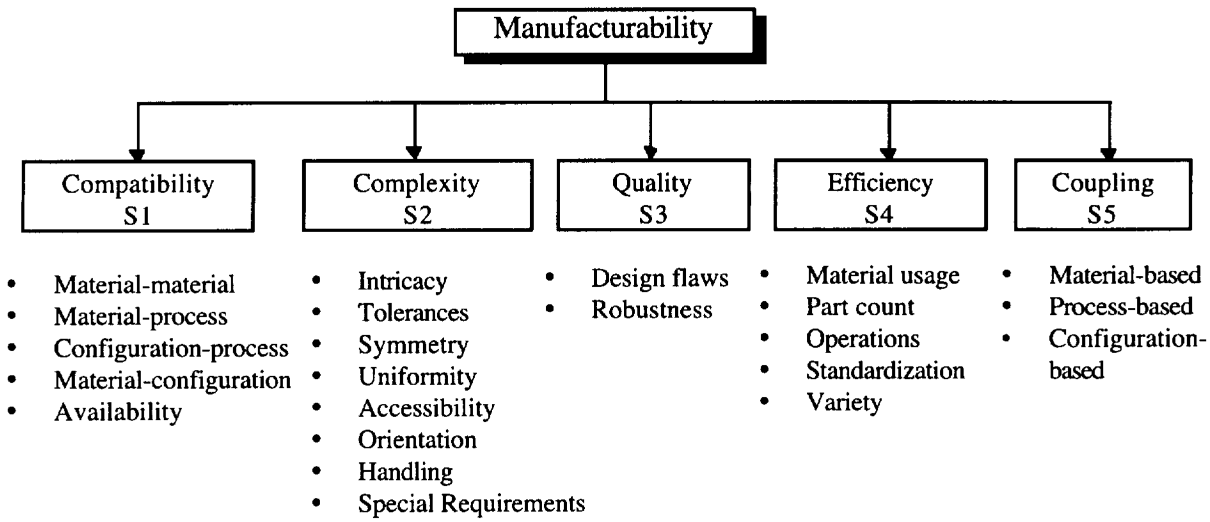


Figure 2. Core Manufacturability Concepts.

While some of the categories in each core, especially those under core 1 such as material-process and configuration-process compatibility, could be addressed at the beginning of the design process, others need to be quantified in a way that allows their inclusion in a multidisciplinary design tool. For example, Kristinsdottir and Zabinsky[10] have considered manufacturing tolerances in terms of the effect of variations of ply orientation angles on the final weight and cost of composite panels. Liang and Heppler[11] have considered another factor related to manufacturing tolerances in terms of the mismatch in the coefficients of thermal expansion in composite panels with plies oriented in different directions.

To quantify the categories under each core manufacturability concept two different metrics will be used: 1. manufacturability measure; and 2. manufacturability index.[9] The manufacturability measure is a metric that is obtained primarily from an analysis of the manufacturing process, whereas the manufacturability index is a metric that is obtained primarily from an analysis of the product, in this case the aircraft structure. To determine manufacturability measures, the process plan is used to identify the tasks which affect the efficiency of the process. For example, the numbers of labor intensive operations, adjustments, tool changes, etc. can be used as measures that allow the designer to identify the design features which make manufacturing difficult or costly. The manufacturability indices are directly linked to the design variables and, as such, can be controlled by the designer. For example, a manufacturability index can be calculated based on the geometrical shape of the structural part.

In the following sections the core manufacturability concepts are defined in more detail. Also, the mathematical models proposed for calculations of some of the manufacturability measures and indices are presented.

S1 Compatibility

When an airframe design is changed as a result of material or process selection, change of configuration, or specification of a tolerance, it is important to check if compatibility has been affected.

With the ability to identify all the structural parts through APaCS (described in Appendix 1), we proceed to examine the processes by which these parts can be manufactured. It may be possible for an airframe part to be manufactured by alternative processes. Hence, it is necessary to have a database containing the name of each structural part and the processes by which it can be manufactured depending on the choice of material system. Two factors have to be considered: (1) whether or not a particular process can be employed to manufacture a specific part, and (2) the limitations associated with each process. As shown in Table S1.1, the processes by which two different types of aluminum wing spars, for example, may be manufactured are marked by an X.

Table S1.1 Two types of aluminum spars and associated manufacturing processes

APaCS #	Integral Machining	Built-Up/ Assembly
0201030201	X	
0201030301		X
0201030601	X	

In this case a one-piece aluminum spar may be manufactured using integral machining process. In order to identify the most suitable process, the limitations associated with each process can be examined based on the available information such as given in Table S1.2.

Table S1.2 Four limitations associated with each process given in Table S1.1

Process	Limitation #1	Limitation #2	Limitation #3	Limitation #4
Integral Machining	high quantity of raw material	the part produced is not very fail-safe	expensive equipment	not repairable
Built-Up/ Assembly	large number of parts	labor intensive	jigging	dimensional variability

The decision as to which one of the acceptable processes should be used to manufacture a given part is made following the examination of part's manufacturability metrics described next.

S1.1 Material-Material Compatibility

Compatibility among the materials used for individual parts is an important issue affecting the quality of the structure and, hence, needs to be considered in the design process. In this section we are only concerned with whether or not the materials chosen are compatible. The issues related to quality are discussed later.

Here, we narrowly define compatibility in terms of any adverse chemical reaction that can occur when parts made of different materials are joined together in the final assembly of the structure. A database of material compatibility is necessary to account for this factor in the design process. The database would contain the list of all possible pairs of materials coming in contact with compatibility or incompatibility identified by 1 and 0, respectively for MMCI, material-material compatibility index. For example, the combination of graphite-epoxy and aluminum alloy would have an MMCI of zero whereas the combination of graphite-epoxy and an alloy of titanium would have an MMCI of one. The incompatibility between aluminum alloy and graphite-epoxy reveals itself in the form of galvanic corrosion in the aluminum part.

A zero value for MMCI should be interpreted as a warning message to the designer to make him/her aware of potential problems that could arise when incompatible materials are joined without incorporating a barrier material of sorts at their interface.

S1.2 Material-Process Compatibility

This category checks the compatibility of a material system with a particular manufacturing process. The material system is identified in terms of its type and form as obtained from a material manufacturer. Since this category is independent of the product, it will be quantified through the manufacturability measure denoted by MPCM1 or the cost measure denoted by MPCM2, which can vary from 1 to 5 with 5 being the best. The first two columns in Table S1.3 identify the material system, the third column identifies the primary manufacturing process, the fourth and last columns give the manufacturability and cost measures associated with the combined selection of material system and manufacturing process, respectively.

Compatibility could be gauged by considering either MPCM1 or MPCM2 values. In the first case the higher the number the better, whereas in the second case the lower the number the better. In comparing the highlighted rows in Table S1.3, we can see that the MPCM1 value is much higher for the combination of 2" graphite-epoxy tape and automatic tape laying process than that using the hand laying process. Likewise, the MPCM1 for the combination of 2" tape and hand laying process is much less than that using the prepreg sheets.

Hence, a database containing information such as the example shown in Table S1.3 could be used in order to give proper consideration to this factor in the design process.

Table S1.3 Material-Process Compatibility Measures

Material System		**Primary Manufacturing Process**	**MPCM1**	**MPCM2**
Type	**Form**			
Aluminum alloy 7075-T6	Sheet	Roll forming	3.0	2.5
Aluminum alloy 7075-T6	Block	Chem. milling	3.7	3.3
Aluminum alloy 7075-T6	Extrusion	Machining	4.0	2.0
Aluminum alloy 2014-T6	Die casting	Machining	4.0	2.0
Aluminum alloy 2014-T6	Forging	Machining	3.5	2.2
Graphite-epoxy AS4-938	2" tape	Automatic laying	4.3	2.2
Graphite-epoxy AS4-938	2" tape	Hand laying	1.0	4.9
Graphite-epoxy AS4-938	Prepreg sheet	Hand laying	3.5	3.7
Graphite-epoxy AS4-938	0.25" tow	Tow placing	4.8	2.4
Graphite-epoxy IM6-3501-6	Roving	Pultrusion	4.8	2.0

S1.3 Configuration-Process Compatibility

The ability of the process to generate the desired part shape and tolerance at an acceptable production rate is referred to as configuration-process compatibility or CPC for short. Machine capacity and cycle time are used to determine the feasibility of obtaining the desired configuration. Machine capacity is used in a process by which the desired geometric form is obtained in discrete steps. Examples of such processes are: stamping, injection molding, resin transfer molding, and superplastic forming. Cycle time is considered in a process by which the part is created in a continuous fashion. Examples of such processes are: machining, chemical milling, and creep forming.

A part's geometrical attributes may be well suited for some processes but impractical for others. For example, machining and forming are two processes that are commonly used for the manufacture of aluminum stringers. The machining process is used for thick stringers and those that are not prismatic. The final shape is obtained by cutting excess material from an extruded beam. Almost any open cross-sectional shape can be produced with machining process. The forming process is used for thin-walled uniform stringers with cross-sectional shapes (e.g., C, hat, and Z) that do not contain what could be called a bifurcation corner. In the forming process the limitations are: minimum radius corner, minimum web width, and maximum thickness.

When the designer specifies a certain cross-sectional shape for the stringer, frame, spar, etc., configuration-process compatibility measures (CPCM) are used as metrics for feasibility and identification of processes that are well suited for each specified geometry. Table S1.4 is a sample of a database that contains information on the part's cross-sectional shape and its variation along the length as well as the processes that would be acceptable to use to manufacture the part.

Table S1.4 Configuration-Process Compatibility Measures

Configuration	Manufacturing Process	CPCM
Hat shape stringer, Non-uniform cross section	Machining	4.0
Hat shape stringer, Uniform cross section	Machining	4.9
Hat shape stringer, Uniform cross section, thin-walled	Forming	3.5
Corrugated rib, thin-walled	Stamping	4.0
Contoured composite skin, Non-uniform thickness	Hand layup	3.5
Contoured aluminum skin, Non-uniform thickness	Machining	4.0
Contoured aluminum skin, Non-uniform thickness	Chem. milling	4.5
Blade stiffened composite skin, Non-uniform thickness	Film infusion molding	4.0

S1.4 Material-Configuration Compatibility

In this case the compatibility of the material system and the part configuration is checked. This is important because the choice of material system may make it very difficult or impossible to achieve the desired configuration. Also in the case of composite materials the layup pattern (i.e., the stacking sequence and fiber direction in each ply) selected for a part can have a serious impact on its final post-cure shape. For example, non-symmetric ply patterns can cause a warping due to a mismatch in the coefficients of thermal expansion of plies having different fiber orientations. While this problem can be easily avoided in the layup of flat plates, it could cause complications in cases of complex geometry.

In the case of metallic structures, it is important to determine the required level of material malleability in forming geometrically complex configurations. The relationship between material properties such as elastic and shear moduli, Poisson's ratio, coefficients of thermal expansion and geometric parameters such as thickness, planform dimensions, and radius of curvature along each axis need to be established in order to determine material-configuration compatibility index, MCCI.

Table S1.5 gives a short list of materials that could be used for particular part configurations. Both the type and form of the material system can influence the MCCI index. The index is assumed to vary between 0 to 5.

Table S1.5 Material-Configuration Compatibility Measures

Material System		Configuration	MCCI
Type	Form		
Aluminum alloy 7075-T6	Block	Hat-shape stringer, Non-uniform cross section	3.9
Aluminum alloy 7075-T6	Extrusion	Hat-shape stringer, Uniform cross section	4.5
Aluminum alloy 2014-T6	Sheet	Flat skin, Uniform thickness	4.9
Aluminum alloy 2014-T6	Casting	Integrally stiffened rib	4.7
Graphite-epoxy AS4-938	2″ tape	Contoured-skin, Non-uniform thickness	3.6
Graphite-epoxy AS4-938	2″ tape	Flat skin, Non-uniform thickness	4.9
Graphite-epoxy AS4-938	Sheet	Contoured-skin, Non-uniform thickness	3.7
Graphite-epoxy AS4-938	0.25″ tow	Contoured-skin, Non-uniform thickness	4.0

S1.5 Availability

This category checks on the availability of various resources required to manufacture an aircraft part. The availability index, AI for a part is determined as the product of the availability factors for all resources necessary to manufacture that part and is expressed as

$$AI = LAF(MAF)(EAF)(CAF) \tag{S1.1}$$

Where *LAF* is the labor availability factor, *MAF* is the material availability factor, *EAF* is the equipment availability factor, and *CAF* is the capital availability factor. Each factor represents the ratio of available resource to the minimum quantity required. Hence, each factor will be in the range of 0 to 1 with 0 indicating unavailability and 1 representing full availability of the resource. A factor cannot exceed 1 even though availability of a resource may be far greater than what is required. If other resources in addition to those stated above are required, their corresponding factors will be placed in the right hand side of Eq. (S1.1) in scalar product form.

Consistent with Eq. (S1.1), *MAF* and *EAF* can each be represented in terms of the specific materials and equipment, respectively, needed for the manufacture of the part as

$$MAF = \prod_{i=1}^{N_{mat}} Maf_i \tag{S1.2}$$

$$EAF = \prod_{i=1}^{N_{eqp}} Eaf_i \tag{S1.3}$$

Where Maf_i is the availability factor for the *ith* material with N_{mat} being the total number of materials needed in the manufacture of the part, and Eaf_i is the availability factor for the *ith* equipment with N_{eqp} being the total number of equipment needed in the manufacture of the part. For example, if a necessary equipment for resin transfer molding is not available, then *EAF* becomes zero which makes availability index zero as well. With AI being zero, then other processes would need to be considered for the manufacture of the part.

S2 Complexity

Complexity factors in structural design can lead to complications in the manufacturing process. Such complications can be measured in terms of increased processing and set-up times, expensive tooling, higher labor costs, and reduced quality. The complexity factors that can affect the manufacturing process are divided into seven categories described next.

S2.1 Intricacy

The amount of detail in a structural part defines its intricacy. We can estimate intricacy by considering the operations that have to be performed in bringing each structural part to its final form. For instance, a metallic wing skin may be first chemically milled on the interior surface to the desired thickness, then age creep formed to the required external geometry. This step then may be followed by cutting out the inspection holes in the case of lower wing skin, etc. The pattern in skin thickness variation per design specifications affects the chemical milling process and can introduce manufacturing complexity. Such intricacy is estimated by calculating intricacy index, II. Next we consider an example for estimating the intricacy index in terms of the features-to-surface ratio F/S.

<u>Example: Determination of Intricacy Index for a Wing Skin With Cutout</u>

In this example the intricacy is estimated in terms of the number of features in a given surface. In particular, we are considering a skin panel with an inspection hole cutout as shown in Fig. 3.

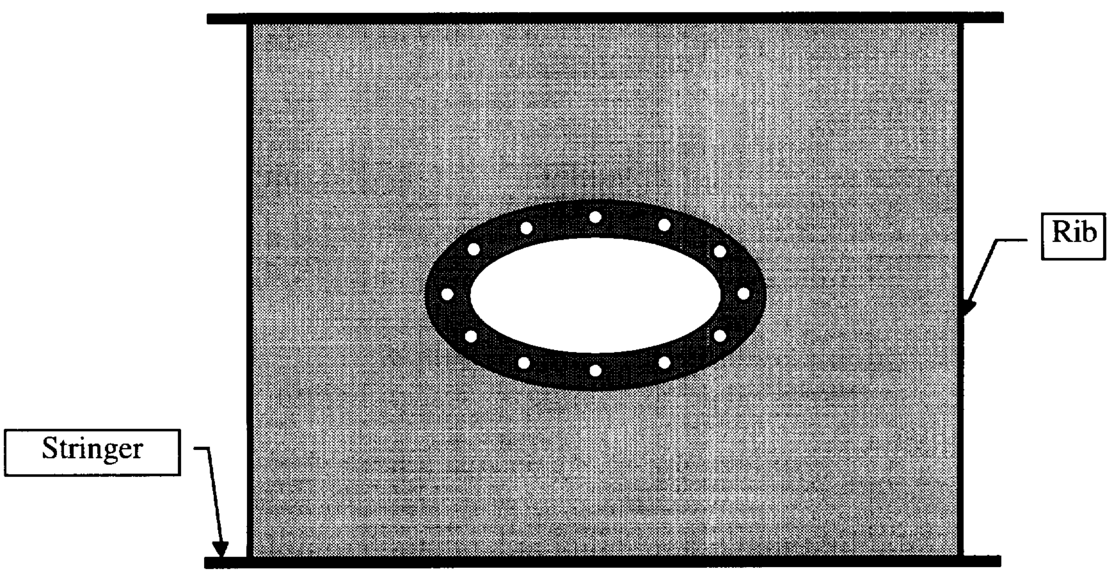


Figure 3. Inspection hole in a skin panel

The internal surface is assumed to be chemically milled and smooth finished only, while the external surface is assumed to be machine milled and smooth finished only around the inspection hole with the entire surface then primed and painted. The thickness variation around the cutout is a feature of both the internal and external surfaces. The thickness around the rim of the cutout is increased on the internal surface and reduced on the external surface to allow for the cover panel to be flush with the skin once the hole is covered. The holes for the bolts are also features attributed to the external surface while the rivet holes to install the lognuts are features attributed to the internal surface. The features of the internal surface are: 1. variable thickness, 2. smooth surface, and 3. rivet holes. The features of the external surface are: 1. variable thickness, 2. smooth surface, 3. primed surface, 4. painted surface, 5. inspection hole, and 6. bolt holes. Hence, the feature-to-surface ratio F/S is equal to 9/2 or 4.5. Based on the data presumably available to the airframe manufacturer for the acceptable and unacceptable levels of intricacy, the intricacy index can be determined using a table similar to Table S2.1. The lower the intricacy index the less complex the manufacturing process is considered to be. In this example the wall surfaces around the holes were not considered in F/S calculation.

Table S2.1 Relationship between feature-to-surface ratio and intricacy index

Feature-to-Surface Ratio (F/S)	Intricacy Index (II)
0	1.0
1-5	2.0
6-10	3.0
11-15	4.0
>16	5.0

S2.2 Tolerance and Surface Finish

The dimensional and geometric tolerances specified in the part design can have significant influence on manufacturing complexity and production cost. Tight tolerances on a structural part require a more sophisticated manufacturing process and more expensive equipment and tools. Also the level of surface finish specified in the part design can influence the choice of manufacturing process and the processing time.

Manufacturing tolerance is a function of equipment accuracy and process used. Two approaches could be implemented in the design process to account for tolerance and surface finish. In the first approach the manufacturing process is identified *a priori*, then the designer varies the shape and size of the structural part according to the attainable tolerance values and determines the effects of these possible variations on structural performance. In the second approach the designer determines the levels of tolerance and surface finish that are acceptable in the design, then the most cost effective manufacturing process capable of satisfying these requirements is identified.

In either approach it is necessary to have a database containing information on attainable tolerances and surface finishes in various manufacturing processes for use in the design process.

S2.3 Symmetry

In terms of engineering analysis and manufacturing, structural parts (e.g., spars and stringers) with cross-sectional symmetry are usually easier to deal with than those with no cross-sectional symmetry. Here is an example where cross-sectional symmetry can be beneficial to manufacturing. Let's consider a built-up spar with four flanges used as caps. If vertical symmetry is imposed, then the flanges on the left side would be identical to the corresponding ones on the right. If in addition to vertical symmetry a horizontal symmetry is also imposed, then all four flanges would be exactly the same. In this case, a single or double cross-sectional symmetry will simplify the manufacturing process in terms of assembly and will reduce the manufacturing costs in terms of reducing variability of parts used in the spar. We will discuss more about variability of parts later in the section on efficiency. The reduction in manufacturing complexity can be partly attributed also to the fact that symmetry in shape would lead to the repetition of the same set of operations with minimal alterations.

To account for the effect of cross-sectional symmetry of individual parts on manufacturing in general, a part symmetry index is introduced. While part cross-sectional symmetry may have large effect on the complexity of some manufacturing processes, it may have negligible effect on the complexity of others. This influence, therefore, has to be known *a priori* for the symmetry index to be meaningful. An equation for part symmetry index is expressed as

$$PSI = \alpha\left(\frac{CSS_{all}}{CSS} - 1\right) \tag{S2.1}$$

Where α is the symmetry weighting factor and its value is based on the manufacturing process being considered. In cases where part cross-sectional symmetry has considerable effect on manufacturing of part, α would be a large number, and in those cases where symmetry has no effect on manufacturing, α would be zero. The range for α in Eq. (S2.1) is assumed to be between 0 and 4. *CSS* is the cross-sectional symmetry factor and it takes a value of 1 if the cross section has no axis of symmetry. If there is a single cross-sectional symmetry, *CSS* is set equal to 2 and for double symmetry *CSS* is set equal to 4. The value of *CSS* doubles for each additional axis of symmetry. The range of values for α and *CSS* have to be calibrated for all manufacturing processes considered in the structural design. CSS_{all} is the maximum cross-sectional symmetry factor allowed in a given manufacturing process. The hypothesis here is that the lower the value of *PSI* the better the design for manufacturing.

Aircraft geometric configurations are commonly made symmetric about the vertical plane passing through the centroid of the aircraft, making the left side the mirror image of the right. If this symmetry of external geometry is duplicated in the arrangement of internal structural parts, additional reduction in manufacturing complexity can be achieved. This reduction in complexity would be manifested in the assembly process where command instructions in automated operations such as drilling and riveting would be simplified. In most structural design procedures attention to layout symmetry is well enforced, hence, no mathematical equation is formulated here.

S2.4 Uniformity

A part is considered uniform if its material and cross sectional properties remain constant along its length. Non-uniformity associated with material and/or geometric variations increases the manufacturing complexity of a part — eliminating some processes from consideration and complicating others.

The skin panels are perhaps the most non-uniform part of the aircraft wing structure in terms of variation in thickness (and ply orientation for composite panels). While introducing non-uniformity in skin thickness may be favorable for structural weight saving, it may contribute to the structures manufacturing complexity and cost increase. Hence, the degree of non-uniformity allowed in the manufacturing process must be known in advance to the designer who can then use that information to establish proper thickness variation constraints in the design optimization procedure.

Additionally, uniformity, or more accurately stated, minimization of non-uniformity in layout of parts may help to reduce complexity in the assembly process. This reduction in complexity may be more pronounced in a manual than in an automated process. For example, the uniform distributions of stringers and to some extent the ribs may help to reduce the assembly complexity of wing structures.

A global non-uniformity index is established here in terms of the non-uniformity index of each designed part and the non-uniformity index associated with layout of parts in the assembled structure. If non-uniformity of parts in an assembly is not an important factor, then the corresponding index is set to zero. An equation describing the global non-uniformity index is expressed as

$$NUI = \sum_{j=1}^{NP} PNUI_j + LNUI \tag{S2.2}$$

Where $PNUI_j$ is the non-uniformity index of designed part j, NP is the number of designed parts in the assembly (such as a wing box structure), and $LNUI$ is the non-uniformity index for the layout. The non-uniformity index for designed part j is determined as

$$PNUI_j = \frac{CNP_j}{MAN_j} \tag{S2.3}$$

Where CNP_j is the calculated non-uniformity of part j and MAN_j is the maximum allowable non-uniformity, which is a function of the material and the manufacturing process used for part j and may take a different value for each process considered. In cases where no non-uniformity is allowed in the manufacturing process, MAN_j in Eq. (S2.3) is set to a very small number instead of zero to avoid computational difficulty.

S2.5 Accessibility

Accessibility is an important factor in assembly operation as well as in post-assembly maintenance inspections and service of aircraft structures. It is, therefore, an important design consideration more so in the case of aircraft wing and empennage structures because of limited volume than in the case of fuselage structures. This limited volume makes access to the internal surfaces very difficult, especially in riveting operations. Automation, however, has significantly reduced the complexity of some of the assembly procedures such as drilling and riveting. In addition to automation, proper scheduling of parts for assembly is used as a method to help reduce the requirements for accessibility in assembly operations.

When access to important regions of the structure for maintenance inspection or repair is limited due to blockage or small volume, access holes are used. For ease of inspection, access holes are usually placed in the lower skin. In airplanes with small wing volume it is necessary to have an access hole in every panel confined between two adjacent ribs. This requirement, however, does not apply to large transport airplanes with plenty of crawl space inside the wings. In the former case the number of ribs and the rib spacing will dictate the number of necessary inspection holes. Hence, by reducing the number of ribs to an acceptable minimum, the manufacturing complexity as well as manufacturing cost of the wing structure will be reduced.

S2.6 Orientation

Orientation refers to the placement of individual parts in a built-up structure such as a wing box. The placements of the ribs and stringers relative to the front or rear spar can be used as a measure of manufacturing complexity. The complexity associated with orientation is twofold: complexity in the required geometric shapes of individual parts based on their orientations in the final assembly; and 2. complexity in the assembly process of these parts to form the final structure.

In the case of straight and untapered wing box, for example, the manufacturing complexity due to orientation is reduced by simply placing the ribs perpendicular and the stringers parallel to the spars. However, in the case of tapered and/or swept wing boxes, the designer has to make a decision as to what orientations of the ribs and stringers relative to the front or rear spar would minimize the manufacturing complexity. Hence, an orientation index is established as a metric for determining the influence of part orientation on manufacturing complexity. The orientation index, *OI* for a wing box is expressed as

$$OI = OIS + OIR \tag{S2.4}$$

Where *OIS* is the orientation index of the stringers, and *OIR* is that of the ribs and are expressed individually as

$$OIS = \left[\sum_{i=1}^{N_{st}} \left(\theta_{st} - \overline{\theta_{st}} \right)_i^2 \right]^{\frac{1}{2}} \tag{S2.5}$$

Where $(q_{st})_i$ is the orientation angle of the *ith* stringer axis relative to a designated spar and the $(\overline{\theta_{st}})_i$ is the most desired orientation angle for the *ith* stringer in terms of manufacturing. The designated spar is specified in the design and may be any of the spars in the wing box. For example, in a multiple-cell wing box where there are more than two spars, the designated spar could be the number two or number three spar. Thus, for a wing box structure the best value for *OIS* is zero.

A similar equation to Eq. (S2.5) is written for *OIR* as

$$OIR = \left[\sum_{j=1}^{N_r} \left(\theta_r - \overline{\theta_r} \right)_j^2 \right]^{\frac{1}{2}} \tag{S2.6}$$

Where $(q_r)_j$ is the orientation angle of the *jth* rib relative to a designated spar and the $(\overline{\theta_r})_j$ is the most desired orientation angle for the *jth* rib in terms of manufacturing. The designated spar could be the same as or different from the one chosen for *OIS* calculation. The best value for *OIR* is also zero.

S2.7 Handling

Part characteristics, such as size, weight, fragility, and shape are factors which affect the handling of the part as it is transported from one machine or operation to another in the manufacturing process. To determine the degree of ease or difficulty of handling a part in the manufacturing process, a special index is introduced. An equation for ease-of-handling index, *EHI* is expressed as

$$EHI = \frac{4}{\left(\frac{S}{S_{\max}} + \frac{d}{d_{\max}} + \frac{W}{W_{\max}} + \frac{V}{V_{\max}} \right)} \tag{S2.7}$$

Where *S* is a measure of part size and is determined as a linear sum of part dimensions along three mutually perpendicular axes with S_{max} representing the maximum permissible value of *S*. If we imagine the part being tightly fitted inside an imaginary rectangular box, then *S* represents the sum of width, height, and length of that box. The parameter *d* is the longest dimension of the part with d_{max} representing its maximum permissible value. The weight of the part is denoted by *W* with W_{max} being its greatest permissible value, and lastly the part volume is denoted by *V* with V_{max} being its largest permissible value. The higher the value of *EHI* the greater the ease of handling of the part. The minimum permissible value of *EHI* is, therefore, 1 with an additional requirement that each ratio in the denominator of *EHI* equation must be less than or equal to 1.

Depending upon whether the part is to be manually or automatically handled, the maximum values for selected parameters such as weight, size, etc., in Eq. (S2.7) may change. Hence, the set of maximum permissible values for these parameters has to be known *a priori* to the designer.

S2.8 Special Requirements

There may be some special requirements in manufacture of a structural part. For example, heat treatment / special processing, hand finishing and hand fit-up, and the use of particular materials could be considered as special requirements. All of these requirements add to the complexity of the structural part and should be adequately addressed in the design phase.

S 3 Quality

Quality of the structure is a measure of how well it performs the function for which it is designed. Issues of importance to quality are design flaws and robustness which are discussed next.

S3.1 Design Flaws

Design flaws are undesirable characteristics, introduced during the design process, which reduce the quality of the structure by adversely affecting its manufacture, use, and/or service and, hence, should be eliminated prior to the submission of the design for manufacturing.

Design flaws are divided into three categories: flaws in design of individual parts; flaws in the design of structural layout; and flaws in the prescribed method of assembly of the final structure. It is important to point out that these categories are not always totally independent of one another. For instance, the method of assembly is affected by the properties of the materials selected for individual parts in the design process. Let's consider a wing structure in which the skin is made of graphite-epoxy composite material and the spars are made of an aluminum alloy. To prevent galvanic corrosion in the spars, it is necessary to place a barrier material between the spar caps and the wing skin before the two parts are permanently joined in the final assembly. In this case, the absence of a barrier material in the assembly process is a flaw that degrades the quality of the assembled structure.

To establish a global design flaw index we need to first create a specific set of metrics for each of the categories mentioned above. For flaws in design of individual parts, the metrics can include structural integrity attributes such as strength, stiffness, and damage tolerance. The designer's choice of material, manufacturing process, and geometric parameters, such as wall thickness in thin-walled members, can affect these metrics. The part flaw index is, hence, expressed as

$$PFI = \frac{1}{3}\left(\frac{ASHM}{RSHM} + \frac{ASSM}{RSSM} + \frac{ADTM}{RDTM}\right) \tag{S3.1}$$

Where *ASHM* and *RSHM* are the actual and required strength measures, respectively; *ASSM* and *RSSM* are the actual and required stiffness measures, respectively; and *ADTM* and *RDTM* are the actual and required damage tolerance measures, respectively. All of these measures are established in the design process and are dependent on the process used to manufacture each part. For instance, bending, torsion, or axial deflection can be used as a measure of stiffness, whereas maximum stress can be used as a measure of strength, and stress concentration factor or residual strength can be used as a measure of damage tolerance. The value of *PFI* is required to be greater than or equal to 1 with each measure ratio in Eq. (S3.1) also required to be greater than or equal to 1.

For flaws in design of structural layout, assemblability, accessibility during and after assembly, inspectability, serviceability, and system compatibility could be used as metrics. The reasons for this selection are as follows. If the parts cannot be joined properly in the assembly process as specified in the design, then we have a flaw in the design. Additionally, if the equipment to be used for assembly require access to a certain region, we have a design flaw if that access is restricted. Inspection, especially in aircraft structures, is a crucial issue. If the parts are assembled together in a fashion that prohibits proper inspection of the assembled structure and prevents adequate service and repair of the structure, then the design is considered flawed. Finally, if the layout design prevents proper placement of non-structural systems such as fuel, control, landing gear, etc., again the design would be considered flawed.

Adequate formulation of an index to account for this type of design flaws is rather challenging. Certainly a CAD drawing of the structural layout would have to be closely examined in order to have a complete assessment of any potential design flaw, such as a curvature mismatch at the surface where two parts are to be joined. With that in mind it may be permissible, however, to propose a simpler albeit less accurate model based purely on geometric attributes. In the case of wing structures, this simple model checks for distances between adjacent ribs for adequate clearance as well as the internal volume in each bay for system requirements. The layout flaw index is formulated as

$$LFI = \sum_{i=1}^{NB} \frac{RS_i}{RS_{\min_i}} + \sum_{i=1}^{NB} \frac{V_i}{V_{\min_i}} \tag{S3.2}$$

Where RS_i is the rib spacing in the *ith* bay with RS_{mini} representing its minimum permissible value while V_i is the usable volume in the *ith* bay with a minimum value given by V_{mini}. The number of bays inside the wing structure is given by *NB*.

For flaws in prescribed method of assembly, material-material compatibility as well as joint strength can be used as metrics. If the joining materials are incompatible, then to avoid any flaws a barrier material have to be used in the contact region.

Depending on what type of joint is used, the area of contact and the wall thickness of parts at the surface of contact have to be adequately designed to prevent any separation or failure at the joint. While contact surface area is the most important factor in bonded joints, the wall thickness of parts and width of the contact area are very important factors in mechanical joints.

The assembly flaw index is written as

$$AFI = \frac{3NP}{\left(\sum_{i=1}^{NP} \frac{JA_i}{JA_{\min_i}} + \sum_{i=1}^{NP} \frac{Jt_i}{Jt_{\min_i}} + \sum_{i=1}^{NP} \frac{Jw_i}{Jw_{\min_i}} \right)} \tag{S3.3}$$

Where JA_i is the contact area of the *ith* part with JA_{mini} representing its minimum permissible value. Similarly, Jt_i and Jw_i are the wall thickness and width of the *ith* part at the region of contact, respectively with Jt_{mini} and Jw_{mini} representing their respective minimum permissible values. *NP* is the number of parts to be joined in the assembly. *AFI* is required to be less than or equal to 1 with each ratio also required to have a minimum value of 1.

The flaw indices defined by Eqs. (S3.1) to (S3.3) are combined to form an equation for the global design flaw index as

$$DFI = \alpha(PFI) + \beta(LFI) + \gamma(AFI) \tag{S3.4}$$

Where α, β, and γ are weighting constants chosen based on the relative influence of each type of design flaws on quality.

S3.2 Robustness

Robustness is referred to the ability of the structure to safely perform the function for which it is designed in the presence of some minor variations in material properties, structural sizing, and assembly. The design is considered robust only if it can perform its desired function under all expected operating conditions.

Engineering constants are considered as the material properties of importance. For orthotropic materials the nine independent engineering constants are: E_1, E_2, E_3, G_{23}, G_{13}, G_{12}, ν_{23}, ν_{13}, and ν_{12}. Where E's represent material's Young's moduli along three mutually perpendicular axes, and G's and ν's represent material's shear moduli and Poisson's ratios, respectively in three mutually perpendicular planes. Subscripts 1, 2, and 3 indicate the three mutually perpendicular principal axes of material symmetry.

Depending on the process by which a material is produced, it is possible to have some variations in its physical and mechanical properties. Such variabilities, however, should not hamper the performance of the manufactured structure. Hence, a structural design would be considered robust if one or all of material properties were degraded by x%, the structure would still be capable of performing its required function. The value of x is chosen by the designer in consideration to the process by which the material is produced and the environment in which the structure is to operate.

The accuracy of the equipment and method of manufacture can greatly influence the final dimensions of the produced parts. The variability in dimensions is more pronounced in parts that are produced via manual rather than partially or fully automated operations. A robust design will accommodate small variations in geometric dimensions stemming from manufacturing operation without significant reduction in the functional capabilities of the structure.

The last element to be considered in regard to robustness of structural design is the assembly-induced variations. Depending on the precision of assembly operation, certain anomalies are to be expected. Rivet spacing and part alignment are two items that could be affected by the assembly operation. A design is considered robust if minor variations in such items do not lead to significant reduction in the structural performance.

A strategy to address the robustness issue in the design process is proposed as follows. In terms of material properties, allowable values can be set at 1 to 5% less than the listed average quantities prior to performing structural analysis and design. For dimensional variations, a method similar to that proposed by Kristinsdottir and Zabinsky[10] for the effect of variations of ply orientation angles on the final weight and cost of composite panels can be adopted here. With respect to assembly-induced variations, a list of potentially troublesome factors has to be established with the help of manufacturing process engineer. The candidate designs will have to be analyzed for robustness by examining the effect of each possible assembly-induced variation one at a time under the whole spectrum of operating conditions. For example, it is necessary to determine how much variation in rivet spacing can be tolerated in the design of a built-up structure in different loading conditions.

S4 Efficiency

Efficiency of the design is not measured by its performance alone as it also depends strongly on its manufacturing requirements. In this section five categories that define efficiency in terms of part design and process selection are identified and discussed. Different examples are used to highlight specific factors affecting efficiency. Also, wherever appropriate a strategy is proposed on how to address manufacturing efficiency in the design process.

S4.1 Material Usage Efficiency

In manufacturing, the efficient use of materials is a function of two factors: the manufacturing process; and the designer-specified geometry for the structural part.

The shaping processes that are mass reducing such as machining and chemical milling could lead to discarding of large amount of material in order to obtain the desired part geometry and size. Discard rate is commonly measured as a percentage of the part's final weight. In machining process the discard rate could be as high as 100%. However, in recent years the airframe industry's efforts in obtaining materials in near net shape has led to a significant reduction in the discard rate associated with the mass-reducing processes. For a specific range of discard rate, Table S4.1 gives the associated efficiency measure, MEM.

TABLE S4.1 : Material Efficiency Measure

Discard rate (%)	MEM (%)
≤5	95
6-10	85
11-25	75
26-40	65
41-65	55
66-100	45
101-150	35
151-200	25

As discussed previously in section S1, material-process and configuration-process compatibility measures along with availability index shorten the list of processes that could be used to produce a part. Now, by examining the estimated discard rates in candidate processes, additional criterion is introduced in helping to identify the most suitable process for a given application.

The second factor contributing to the efficient use of material is part geometry, which is more directly influenced by the designer. If the part is designed larger than necessary or in a geometric shape that is unnecessarily complex, then a lot of material would have to be wasted in its manufacture. Structural optimization could be used as a tool to minimize the size and complexity of structural components thereby reducing its weight and manufacturing cost.

S4.2 Part Count

Assembly process is one of the most expensive elements of manufacturing — one that is directly linked to the number of parts and how they fit in an assembly. Therefore, in an effort to reduce the assembly cost, the number of parts or part count should be reduced. This reduction in part count is advantageous as long as it does not result in a substantial increase in complexity of remaining parts. Otherwise, the benefits of lower part count in manufacturing would be negated with additional process steps and labor requirements.

The aircraft parts classification system (APaCS) described in the appendix could be used to keep track of structural parts in an assembly and identify those parts whose elimination could increase manufacturing efficiency. As a general rule, a reduction in the number of larger parts leads to a reduction of numerous smaller parts. For example, by reducing the number of stringers in the wing box, a substantial number of rivets and clips could also be eliminated.

In addition, the choice of material system could lead to a significant reduction in the number of parts. This has always been the major selling point of composite materials over metal alloys. The fabrication methods for composite materials are such that many of the major parts can be either cobonded or cocured in the fabrication process and as a result fasteners that comprise the majority of parts in built-up structures could be eliminated.

Example: Comparison of Three Wing Box Structures for Part Count Efficiency

To illustrate the effect of structural design concepts on associated part count we consider three different wing box designs as shown in Fig. 4. In the first design shown in Fig. 4(a) the wing box is of skin-stringer type with the upper and lower skins stiffened with a number of Z stringers. In the second design shown in Fig. 4(b) the wing box utilizes sandwich skin thereby reducing the requirement for the number of stringers. In the third design shown in Fig. 4(c) the wing box is of a multi-spar configuration with the spar caps supporting the skins. These three designs are assumed to be fully capable of carrying the required loads, however, each does it in a different way and with different number of parts and associated complexity. We are assuming here that requirements for structural integrity and reliability are adequately satisfied by all three design concepts.

Comparing designs (a) and (b) we observe that the number of stringers is less in (b); however, the skin design in (b) is more complicated than the one in (a) and requires more parts to build. Design (c) has no stringers, but it has two additional spars compared with designs (a) and (b). In design (c) as in design (b) additional complexity has accompanied the reduction or removal of stringers. The most efficient design would be the one with the best balance between complexity and part count.

The efficiency index in terms of part count could be expressed as

$$PCEI = \sum_{i=1}^{N} C_i \tag{S4.1}$$

where C_i is a measure of complexity (e.g., intricacy factor) associated with each part and N is the total number of parts in the assembly. In case of common complexity measures in each set of parts, Eq. (S4.1) reduces to

$$PCEI = N_{sk}C_{sk} + N_{st}C_{st} + N_{sp}C_{sp} + N_rC_r \tag{S4.2}$$

where N denotes the number of specific parts with common complexity measure. The subscripts *sk*, *st*, *sp*, and *r* refer to skin, stringers, spars, and ribs, respectively.

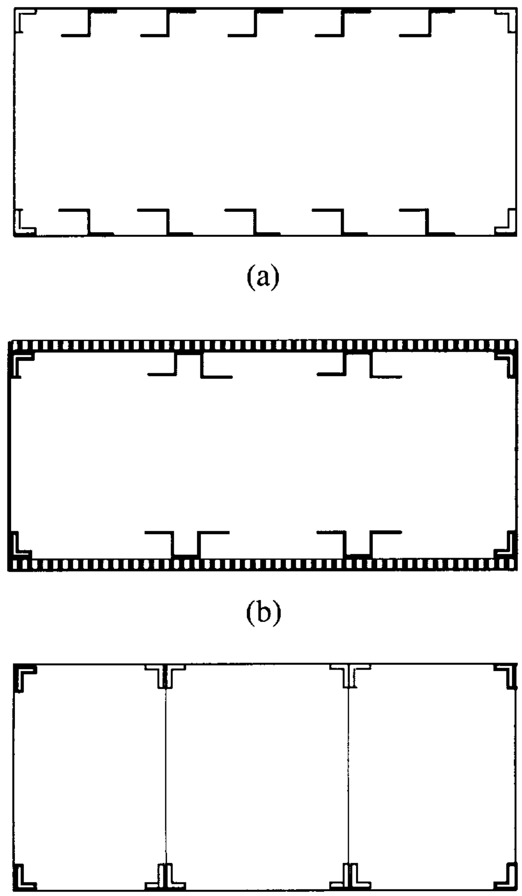
If the skin, spars, and ribs have to be individually assembled prior to final wing assembly, then the assembly efficiency index could be expressed as

$$AEI = AE_{sk} + AE_{sp} + AE_r + AE_a \tag{S4.3}$$

Where AE_a denotes the wing assembly efficiency index. The overall efficiency index is, therefore, expressed as

$$PCI = PCEI + AEI \tag{S4.4}$$

The efficiency of each wing design could then be judged based on the associated *PCI* value.



(a)

(b)

(c)

Figure 4. Comparison of Three Different Wing Box Designs in Terms of Part Count Efficiency

S4.3 Operations Efficiency

The operation efficiency is generally fixed for each process on a particular machine. The efficiency here refers to the accuracy by which the required feature is produced in a given operation. For example, drilling operation if performed by lathe has a different efficiency from that performed by a drill machine. In a drill machine a hole can be drilled more accurately as compared to a lathe due to the fact that in drill machine the tool is rotating where as in lathe the part is rotating. In general, depending upon the tolerances specified, it may be possible to use a simpler process or eliminate an expensive operation to increase efficiency of manufacturing.

In order to establish an operations efficiency index, it is necessary to have an accurate list of operations that would be performed in each specific manufacturing process. Once equipped with a good knowledge of the manufacturing process flow, the designer with the help of manufacturing engineer ought to be able to identify key features which reduce operations efficiency, and work toward their elimination in the design process.

S4.4 Standardization

Manufacturing efficiency can be greatly enhanced through the use of standard parts, materials, processes, and tools. In the case of aircraft structures, standards include the shape and size of stringers and fasteners, material systems, and well tested manufacturing processes. Whether a structural part is produced in house or purchased from a vendor, the use of standards increases manufacturing efficiency and helps to lower the manufacturing costs. Standardization is complemented by uniformity requirement, discussed in section S2, and is also supported by availability requirement discussed in section S1.

Enforcement of standardization in an optimization procedure leads to introduction of discrete variables which are difficult to manipulate. Instead, it would be easier to perform *a posteriori* analysis following the completion of the design optimization procedure in which parts' sizes are treated as continuous variables. By increasing the optimum sizes to standard values a more efficient design in terms of manufacturing would be obtained.

S4.5 Variety

One way to increase manufacturing efficiency and lower costs is to reduce variation in common parts. This reduction in part variation allows an increase in lot size and, hence, will reduce both manufacturing cost and complexity. The designer should consider, for example, using identical stringers in aircraft wing and identical rings in aircraft fuselage structures as much as possible. A reduction in variety, however, may lead to excess structural weight as larger standard parts are used in place of smaller parts. Hence, material use efficiency discussed earlier will have to be balanced with an increase in manufacturing efficiency introduced through the reduction in part variation.

The discussion here also sheds some light on often overlooked fact that a minimum weight design is not necessarily a minimum cost design as in the first case part variety is encouraged. The strategy discussed for including standardization of parts in the structural design could be expanded to include limits on variation among common parts.

S 5 Coupling

Coupling refers to the condition in which changes in one or more parameters have opposite effects on the functional and production requirements of the design. The variables that have such an effect on the design are referred to as coupling variables. In this section three different categories for coupling are discussed.

S5.1 Material-Based Coupling

Material-based coupling is found mainly in anisotropic materials such as fiber reinforced composites. In these materials mechanical properties such as Young's modulus and physical properties such as coefficient of thermal expansion in the direction of the fibers are different from the corresponding values in other directions. While the dependence of material properties on fiber direction is used as a tool to improve the functional requirements such as stiffness and strength, its improper use could lead to complications in the manufacturing process. For example, part geometry and/or the specified method of fabrication may prohibit the placement of fibers as specified in the design. Limitations such as this must be considered in the design to avoid difficulties in production.

Fortunately, most of the manufacturing restrictions due to material-based coupling can be adequately addressed in the design process as well as in the optimization procedure through the use of manufacturing constraints or upper and lower bounds on coupling variables.

S5.2 Process-Based Coupling

The process-based coupling stems from factors rooted in the manufacturing process. As in the case of material-based coupling the coupling variables could have opposite effects on functional and production requirements of the design.

For example, an important factor in the fabrication of thermoset matrix composite parts is the cure cycle, which refers to the period a part has to stay inside an autoclave under varying levels of temperature and pressure until the matrix material is cured. Improving the cure cycle as in reducing the cure time and/or reducing the cure temperature could lead to increase in production rate and decrease in manufacturing costs. However, if the part is removed too early or cured at too low a temperature, then the strength and stiffness properties will not meet the design specifications, rendering the part useless.

S5.3 Configuration-Based Coupling

The aim here is to identify and properly handle the design features that are the source for this type of coupling. These features may include part size, corner radius, wall thickness, and number, shapes, and locations of holes in the part. If quantitative measures relating design features to process parameters are available, then it would be possible to properly handle these design features in the optimization procedure. In the absence of such models, only qualitative assessments can be made in the design

Future Work

Prior to integrating above mentioned factors into a computational design tool, several airframe companies will be contacted to help identify the most important factors to keep and those that could be eliminated from consideration. We will conduct further refinement of the proposed models and validate them with the help of industry.

We will also examine different cost estimating methods and the procedures by which cost assessments could be addressed at every stage of the design process.

Furthermore, we will investigate the organizational requirements and development of what could be considered as a **d**esign **gu**ide and evaluation **t**ool (DIGIT). The help of software companies will be sought in this regard.

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Appendix

Aircraft Parts Classification System

Aircraft parts can be systematically classified using the Aircraft Parts Classification System (APaCS) based on the approach reported by Hill *et al.*[12] APaCS is a five tier classification system. The five tiers or levels can be differentiated based on the identity of the system and its components with each level contributing to the formation of the level above it. The level numbers indicate the degree of refinement in parts classification. The higher the level number the higher the breakdown of system into its smaller constituents.

The 10 digit coding system shown in Fig. A.1 allows every part to be uniquely identified. Each level has two digits assigned to it in the APaCS nomenclature assuming there are no more than 99 entities at each level. For example, the code for the right wing as a whole would be 0200000000. The code for the fuel bladder inside the right wing would be 0208020000. This code can be interpreted by the fact that the fuel bladder belongs to the right wing which is identified by 02 in level 1 and fuel system in level 2 identified by 08 with level 3 entity or primary part number in this case being 02 (bladder). If multiple fuel bladders are used inside the wing or additional parts are involved, then the remaining digits can be used to make further classification.

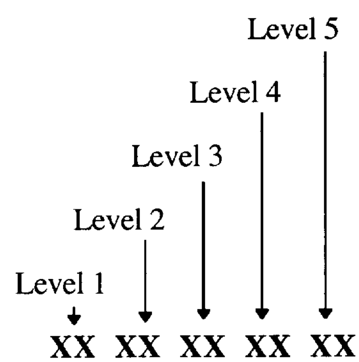

Figure A.1 Code Pattern in APaCS

Level 1 Classification:

The level 1 of APaCS aims at identifying the system under consideration. For example, an aircraft wing would be considered a level 1 entity in APaCS. The level 1, in general, consists of the following systems:

0100000000 = Fuselage
0200000000 = Right Wing
0300000000 = Left Wing
0400000000 = Right Horizontal Tail
0500000000 = Left Horizontal Tail
0600000000 = Vertical Tail
0700000000 = Nose Gear
0800000000 = Left Main Gear
0900000000 = Right Main Gear
1000000000 = Engine 1
1100000000 = Engine 2
1200000000 = Engine 3

1300000000 = Engine 4
1400000000 = Avionics

APaCS allows up to 99 system specifications in level 1. Here the emphasis is placed primarily on the airframe systems.

Level 2 Classification:

Level 2 identifies the major subsystems incorporated in each system in level 1. It is possible to have up to 99 different subsystems in level 2. For Example, the right wing can be divided into 11 subsystems as:

0201000000 = Wing box
0202000000 = Control surfaces
0203000000 = Propulsion support
0204000000 = Main landing gear support
0205000000 = Deicing
0206000000 = Mechanical
0207000000 = Hydraulic
0208000000 = Fuel
0209000000 = Electrical
0210000000 = Fairing and covers
0211000000 = Chemical (primer, paint, etc.)

Level 3 Classification:

At this level all the parts needed to fully define each subsystem are described. In the case of the right wing box, the primary parts can be represented as:

0201010000 = Upper skin
0201020000 = Lower skin
0201030000 = Spars
0201040000 = Ribs
0201050000 = Stringers
0201060000 = Clips
0201070000 = Fasteners
0201080000 = Sealant
0201090000 = Shims

Each one of the parts can be further defined by its individual segments using the first digit associated with level 3 or the two digits associated with level 4. For example, we can make a distinction between the fore (0201130000) and aft (0201230000) spars using the first digit of level 3 while web and cap specifications can be made using the level 4 digits.

The primary parts of the control surfaces subsystem (0202000000) are:

0202010000 = Flaps
0202020000 = Ailerons
0202030000 = Spoilers
0202040000 = Slats

The primary parts of the propulsion support subsystem (0203000000) are:

0203010000 = Support structure

0203020000 = Nacelle

The primary parts of the main landing gear subsystem (0204000000) are:

0204010000 = Support structure

The primary parts of the deicing subsystem (0205000000) are:

0205010000 = Hardware

The primary parts of the mechanical subsystem (0206000000) are:

0206010000 = Linkages
0206020000 = Hinges
0206030000 = Bearings
0206040000 = Shafts
0206050000 = Couplings

The primary parts of the hydraulic subsystem (0207000000) are:

0207010000 = Pumps
0207020000 = Hoses
0207030000 = Pipes

The primary parts of the fuel subsystem (0208000000) are:

0208010000 = Hoses
0208020000 = Pipes
0208030000 = Bladders

The Primary parts of the electrical subsystem (0209000000) are:

0209010000 = Actuators
0209020000 = Sensors
0209030000 = Wiring
0209040000 = Lights
0209050000 = Antennae

The primary parts of the fairing and covers subsystem (0210000000) are:

0210010000 = Wing/Fuselage fairing
0210020000 = Leading edge fairing
0210030000 = Trailing edge fairing
0210040000 = Engine support fairing
0210050000 = Control linkages fairing
0210060000 = Landing gear door
0210070000 = Access panels
0210080000 = Wing tip cover

The primary parts of the subsystem (0211000000) are:

0211010000 = Priming
0211020000 = Painting
0211030000 = Corrosion resistance

Level 4 & 5 Classifications:

In Levels 4 and 5 the parts characteristics in terms of the type of part and material are identified. For example, a wing spar can be further classified in terms of its construction type and material system used as shown below:

0201030100 = Flat web, assembled spar
0201030200 = Flat web, one-piece spar
0201030300 = Sine-wave web, assembled spar
0201030400 = Sine-wave web, one-piece spar
0201030500 = Truss, assembled spar
0201030600 = Truss, one-piece spar

The wing spar classification by type and material system:

0201030101 = Flat web, all aluminum, assembled
0201030111 = Flat web, aluminum web, steel caps, assembled
0201030121 = Flat web, al. alloy 1 for web, al. alloy 2 for caps, assembled
0201030201 = Flat web, all aluminum, one-piece
0201030241 = Flat web, all composite, one-piece

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0201030301 = Sine-wave web, all aluminum, assembled
0201030341 = Sine-wave web, all composite, assembled

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0201030501 = Truss, all aluminum, assembled

As can be seen with the above classification, it is possible to have up to ten different material systems for each type of spar.

The numbering system introduced here allows each part in the design process to be cataloged into a database making it easier to include manufacturing and cost requirements in the structural design process.